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HYDROLOGICAL BASIS FOR FORECASTING AND CALCULATING RUNOFF BY SPACE IMAGES OF THE EARTH'S SURFACE

G. P. Kalinin

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HYDROLOGICAL BASIS FOR FORECASTING AND CALCULATING RUNOFF BY SPACE IMAGES OF THE EARTH'S SURFACE

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Introduction

The prospects for realizing the capabilities of development of hydrology which have appeared in connection with man's mastery of space are determined by the level of development of space science, its ability to set and solve new problems, most effectively utilizing the development of this new system for the study of nature today and tomorrow. At the present time, the following important problems of hydrology have developed: /2*

1) determination of the processes of evolution of natural waters leading to their contemporary state, both on Earth and in space;

2) development of new methods for studying the dynamics of surface, soil and underground water in various phase states.

The pressing nature of the first problem can be clearly seen from the singular status of the Earth's water envelope in contrast to those of the other planets, which in the final analysis is one of the main reasons for the development of life of Earth. The most important thing here is establishment of the causes which have defined the relationship between the arrival of moisture to the surface of the planet from below and its dissipation into space.

The difficulty of solution of this problem consists not only in the fact that this situation is influenced by differences in the massesof the planets and their distance from the sun, but, and even primarily, the extreme difficulty of even approximate estimation of the process of arrival of water at the surface of the Earth and water exchange with space. /3

It is quite probable that the appearance of water over even a small portion of the surface of the Earth at some time in the distant past facilitated the development of the biosphere which, in contrast to the other planets, resulted in a transformation of the gas composition of the atmosphere and the "creation of the shield," retarding the transfer of water into space and creating conditions for an increase in the quantity of water on the surface of the Earth.

The stratospheric water vapor trap created during the process of evolution of the Earth (related to the presence here of ozone),

*Numbers in the margin indicate pagination in the foreign text.

preventing the upward diffusion of water vapor, is an extremely fine mechanism, which arises under a very limited range of physical conditions, since of all the planets of the solar system it apparently functions in this form only on Earth. The importance of studying this mechanism is reinforced by the fact that the intensive interference of man in the life of nature could possible create conditions leading to its disruption.

The production of new data on the distribution of water and factors of its formation in space and on the planets, and the study of the water exchange of the other planets will help to solve this problem.

As concerns the second problem, there are a number of areas of hydrological science interested in the development of remote methods of investigation. They include in particular:

1) calculation and prediction of the formation of runoff; /4
2) pollution of bodies of water;
3) the thermal modes of bodies of water and the ice caps;
4) dynamics of the snow cover and glaciers;
5) the moisture reserves in the atmosphere and the soil;
6) the levels of underground waters, the delivery of underground waters to the lakes, seas and oceans;
7) erosion of soil and shorelines, the structure of the contemporary and ancient river network, etc.

Even this incomplete list indicates the great interest felt in remote methods of investigation. However, most works dedicated to this type of study are quite narrow in scope or merely record the peculiarities of some phenomenon on photographic images. In connection with this, theoretical analysis and practical utilization of the new information fall far short of our capabilities. At the present time, there is no shortage of general discussions on the usefulness of remote methods. However, their practical application has achieved considerably less success than would be expected. Therefore, let us abandon further general discussions and concentrate our attention on the development of specific methods for the utilization of remote observations in the area most familiar to the author -- methods of prediction and calculation of runoff.

Analysis of the contemporary state of this area has shown that we have the ability to create a new, more precise system or predicting hydrological processes, based both on the logic of development of hydrology, and on new methods of production and new typesof information. In order to make more convincing the practical reality of these suggestions, I have intentionally, as much as possible, avoided controversial questions and have used to the /5 maximum as the component elements of the calculations those methods of prediction which have been tested many years in practice.

The more intensive the development of any given branch of natural science, the greater the requirements which it places on the form and accuracy of new observations. It is therefore to be expected that in this work, concerned with a rapidly developing branch of science, many new experimental studies and observations are needed.

The primary points of the present work can be summarized as follows:

1. Although the objects of study of continental hydrology are processes of formation of water on the surface of the Earth, the primary souces of information used have been the individual point observations of weather stations which, due to the limited territory which they observed, cannot provide sufficiently complete information on the dynamics of the processes studied. Direct observation of the dynamics of hydrological processes over territories of various scales can significantly improve the knowledge available on the processes in question and the accuracy of calculations related to these processes.

2. The generally accepted theory of the formation of runoff, in combination with certain empirical data, allow us to use the materials of observation to produce the transition functions from hydrometeorological point observations to runoff. The so-called genetic runoff formula is so general in nature that in principle (with some modification) it can be applied to the new information produced from space photographs as well. This allows us to use the known apparatus for the solution of a broad range of hydrological problems, involving qualitatively new information.

3. Flooded areas (surfaces of basins, the networks of gulleys, ravines and rivers) and the extent of the contemporary stream network find themselves in a near functional relationship with the hydraulic characteristics of these terrain elements, as well as the runoff of water from them. Although the structure of these connections is still not fully understood, by using the broad experience gained in solving reverse problems, they can be established in principle on the basis of analysis of observational material. /6

4. Various examples of the characteristics of filling of the surfaces of water basins, as well as the gulley, ravine and river networks, allow us to use in our calculations, depending on the resolving capacity of our apparatus, various types of initial observational material. This provides great flexibility for the use of photographs if a system of methods of prediction and calculation is developed allowing us to use photographic images of various scales as necessary.

5. The runoff from the surface of a basin in the final analysis amounts to the difference between precipitation and

losses. These elements, particularly runoff losses, are determined quite roughly for a number of reasons, leading to great errors in the predictions and calculations. However, the areas of coverage of the surface of a basin with water determined from photographic images can be thought of as a result of the transformation of this difference of precipitation and runoff. This creates the prerequisites for avoiding such rough characteristics in our predictions and calculations and using more direct runoff factors as initial data. In particular, we should emphasize the unique nature of the characteristic of the flooded area of a basin surface, which is simultaneously an indication of the supply of surface and underground waters.

6. This creates the possibility in principle of restructuring the contemporary system of predictions and calculations to another, logically related, system using the new information. /7

7. The great significance of the new capabilities for prediction will stimulate the development of new experimental studies of the surfaces of basins, the structure of the water network, and the complex of hydrological processes occurring in it. A particular role here must be played by experimental areas, which should be set up to allow surface observations, observations from stationary towers (photographic observations, observations of terrestrial radioactivity, etc.), as well as observations from aircraft and satellites at various altitudes.

1. Methodological Basis for the Prediction of Runoff from Images of Stream Network and Basin Surface Flooded Areas

Remote methods can most easily observe the characteristics of processes occurring on the surface of a basin (in particular, the area covered by water).

On the other hand, there is a close and unambiguous connection between the dimensions of the flooded area and subsequent values of runoff through the closing line of a river.

Thus, the problem of investigation of predictions and calculations of runoff by remote methods can be reduced to:

a) establishment of the direct dependences between the areas of coverage of basin elements studied with water and runoff characteristics;

b) establishment of the characteristic dimensions of areas of coverage of the surface of the elements studied with water under various hydrological conditions; /8

c) determination, according to the resolving capacity of the apparatus, of the accuracy of measurement of these areas or their integral characteristics by remote methods now and in the future.

The first two of the problems listed above relate fully to the area of hydrological investigations. In the last problem, the role of hydrology is reduced to establishment of the requirements for remote investigations in order that hydrological problems might be solved with the necessary accuracy.

As will be shown below, the variety of processes of formation of runoff and the strict sequence of their development in time ereate quite favorable conditions for broad utilization of remote methods.

Actually, in the first phase of formation of runoff after water arrives at the surface of the basin, the low-lying and poorly filtering portions of the basin are immediately flooded. This means that a network of tiny lakes of various sizes, both drained and undrained, is formed on the surface of the basin. The curve of distribution of the areas (F) of drained and undrained microlakes is a function of the reserves of water on the surface of the basin or of the slope runoff which changes little with time. The total area covered with water can be represented as

$$F_{tot} = f(W) \text{ or } F_{tot} = \psi(q_{sl}).$$

The dimensions and areas of individual microlakes depend on the constant physical-geogrphical conditions (particularly the slope) of the terrain and the time-variable conditions of runoff formation. The smaller the dimensions of the microlakes, the more of them there are. The range of fluctuation of dimensions of microlakes is quite great: from those whose areas are fractions of a square meter up to microlakes having areas of hundreds of square /9 meters to several square kilometers. The dimensions of microlakes increase during heavy rains.

The areas of coverage of the basin surface with microlakes, measured remotely, can be used to characterize:

a) the total area of microlakes for the basin, the dimensions of which exceed the resolving capacity of the apparatus;

b) changes in reflectivity due to changes in the total area of the microlake water surface.

In order to develop a method for solution of these problems, we must combine surface and remote observations. In particular, we note that since the microlakes are all filled at the same time by the same causes, there should be a close relationship between the total area of the basin covered by water and the area of the greatest flooding. Of course, this relationship is individual for each basin.

At the same time, we should note that the less the overall slope of the basin and the greater the intensity of the runoff, the greater the dimensions of the areas of the basin covered by water. This means that the most favorable conditions for prediction of runoff with this approach are those following high floods flat basins.

One of the main difficulties of determination of changes with the area of a basin covered by water with time is the brevity of the process, which is frequently measured in hours or days, requiring very frequent measurements.

With the frequency of measurement of natural resources by satellite on the order of twice per month, it is impossible to trace the dynamics of the areas of surface covered by water.

A satellite of this sort can be used to evaluate the dynamics /10 of soil moisture content, which changes considerably more slowly. For many hydrological problems, the frequency of measurement by satellite during some phases of the hydrological mode should be the same as for a weather satellite, and in some cases even more frequent measurement is needed.

The second phase of formation of runoff consists in delivery of water to ravines and dry valleys.

During floods, rather significant streams of water may be formed in dry valleys, since the water shed area of a dry valley is usually 5-10 km^2 if the terrain relief is greatly broken, and up to 20-25 km^2 is the relief is less broken. The process of formation of runoff is longest here.

It should be noted that the transition from one phase of runoff to another extends over some period of time.

The next phase is gradual formation of the runoff in rivers of first, second and higher orders. Investigation of the structure of the river network has been the subject of a number of works [33, 27, 22, 24] [R. Horton, N. A. Rzhanitsyn, L. D. Kurdyumov, R. Ye. Nezhikhovskiy and others).

In agreement with R. Horton, we will consider the smallest stream with no tributaries a first order river, a river formed by the confluence of two first order rivers a second order river, etc.

R. Horton has established the following regularities:

$$N_\theta = E_N^{\phi-\theta} \text{ and } \overline{L}_\theta = L_1 E_L E^{\theta-1},$$

where N_θ is the number of tributaries of order θ in a given basin, /11
ϕ is the order of the primary river, E_N is a parameter varying from 2 with flat relief to 4 in mountain regions, $\overline{L}$ is a parameter, E_L is a parameter with a mean value of 2-3. N. A. Rzhanitsyn [27] has produced a relationship allowing us to determine the area and length of rivers.

We should emphasize the influence of map scale. For example, according to B. P. Panov streams of order 1 on a map of 1:1,000,000 scale may have order 3-4 on a map of 1:1,000,000 [sic -- tr.]. The mean length of a stream of order 1 for the European portion of the USSR on a 1:1,000,000 scale map is 5 km, on a 1:25,000 scale map -- only 0.6 km.

The distribution of rivers of various orders has common features for different territories.

Depending on the resolving capacity of the remote measurements, the initial elements for which the area of the surface of a river is determined should be rivers of various orders and, consequently, with varying indicators and dimensions of the characteristics of the surface runoff. Actually, as was mentioned above, the slope runoff may be characterized either by the flooded surface area of the basin covered by microlakes with dimensions greater than the resolving capacity of the apparatus, or the reflectivity of the entire basin surface if the surface of the basin is covered by tiny lakes. The filling of the gulley, ravine and stream network is characterized by the area of streambed and pond flooding.

It should be kept in mind that the interpretation of space photographs is being successfully used even now to determine the morphometric characteristics and evaluate river modes. /12

Standardized interpretation of space photographs performed for a number of regions shows that they reflect practically the entire river and lake network [30]. The good coverage of these photographs allows the structure of the network as a whole to be studied. /12

Prominent rivers can be seen on these photographs even if they are small (less than 10 km), the beds clearly reflected in all details. Space photographs allow reliable recognition of temporary streams, which appear as light grey, extended, sometimes meandering bands. Space photographs show the boundaries of the flood plain of a river, noted by a general darkening of the tone, in significantly better detail than large scale maps. Therefore (particularly in cases of catastrophic floods), the use of space and aircraft photography may facilitate more precise prediction.

2. Determination and Prediction of Surface Runoff from Area of Coverage of the Surface of a Basin with Water

The value of surface influx of water in a river network (q) and the volume of water (W) located on the surface of the basin are connected by a near-functional relationship:

$$q = f(W) \tag{1}$$

on the other hand there is also a near-functional relationship between the area covered by water ω and W

$$w = \phi(\omega). \tag{2}$$

From this

$$q = \psi(\omega) . \tag{3}$$

Thus, in order to determine the influx of surface water to a river network, two problems must be solved: determination of the percentage of the area of the basin covered with water and determination of the form of the relationship between the size of this share of the area and the influx of water to the river network.

The first portion of this problem is sovled by the methods of /13
aerial and space photography either by direct determination of the areas covered with water or by determination of the mean reflectivity of the surface of the basin. In the latter case, the preliminarily established relationship between these changes and the degree of coverage of the area of the basin with water is used.

Determination and prediction of surface runoff on the basis of areas of various degrees of soil moisture may be quite promising for future studies. At the present time, methods have already been developed for determination of reserves of water in the upper layer of the soil by gamma surveying on the basis of aircraft observations [26, 42].

A judgment on the moisture content of the soil can also be made on the basis of satellite images in the visible light range, Even comparatively low spatial resolutions such as those provided by an element of a television image on the order of 1 km in length are sufficient for the study of the regional moisture field. It is shown in [reference omitted -- tr.] that there is a very good correlation between the albedo of soils of various moisture contents and the density of the negative image, allowing the moisture content of the soil to be determined from the intensity of the signal of a television image.

Examples of refinement of the contours of precipitation and the boundaries of soil moistening using color photographs produced by the Gemini-4 spacecraft are promising for the study of rain flooding [reference omitted -- tr.].

New possibilities for determination of the quantitative characteristics of soil moisture are provided by the use of methods of passive radar study in the centimeter wave band. According to [references omitted -- tr.], measurements in the microwave band at /14 wave lengths of 3.4 and 8.5 cm have established a decrease in radio brightness temperature with an increase in soil moisture content, which is linear in nature. Recently, a number of works have appeared (references omitted -- tr.], in which attempts have been made at quantitative determination of the moisture content by solution of the reverse problem of determination of the physical parameters of the soil on the basis of its thermal radiation field.

Of greatest interest for purposes of hydrological prediction is estimation of the distribution of the quantity of moisture in the soil by depth based on measurement of radio brightness temperatures at wave lengths of 0.81, 2.2, 6.0 and 21.4 cm [32].

The second part of the problem can be solved by two methods or by a combination of the two: the first consists in theoretical-experimental determination of the form of the relationship $q = \psi(\omega)$, while the second is based on solution of the reverse problem -- establishment of $\omega(q)$ by observation of ω and q. It would seem that the problem could be solved by the first method by using theoretical constructions for calculations of the slope runoff, but in the overwhelming majority of cases they are based on the conception of a continuous slope runoff. This approach is useful for certain calculation plans, but in this case it is quite inapplicable, since the method is based on incomplete coverage of the basin with water, the conditions which occur in nature.

Therefore, development of a theory considering the noncontinuous nature of the formation of surface runoff and experimental study of the structure of the surface of the basin and related runoff consitions is of great significance. Here it is first important to determine the form of the relationship $q = \phi(\omega)$, while establishment of the distribution curve of the capacity of undrained depressions included as one of the most important aspects of the /15 theoretical construction is also significant. Let us study this latter point first.

If we imagine a slope with inclination i, on which there are a number of depressions limiting runoff, then the volume of depressions per unit of width with slight runoff will be equal to

$$W = \frac{H^2}{2i}. \tag{4}$$

From (4), we find

$$H = \sqrt{2iW}. \tag{5}$$

If we know the distribution curve f(H), the corresponding distribution curve of volumes $\phi(W)$ is expressed by the relationship

$$\phi(W) = \frac{i}{H}f(H). \tag{6}$$

We can see that with even arbitrary normality of the distribution function of depths of the water layer f(H), the distribution curve of capacities $\phi(W)$ will be sharply asymmetrical. On the other hand, clearly with otherwise equivalent conditions the area covered by water will be greater, the less the slope. We can assume that in many cases the regularities noted above will also be correct to some extent for the volumes of water with drainage through individual elevations, since the layer of water pouring over the elevations may be significantly less than H. The curves of distribution of area ω should be similar in nature to the curves for distribution of H, since the area per unit width is

$$W = \frac{H}{i}. \tag{7}$$

The total influx of water to the river network can be approximately expressed by the relationship

$$q = cS\bar{H}^{1+2/3}i^{0.5}, \tag{8}$$

where c is a parameter, $\bar{H}$ is the mean depth of the flow near the river network, S is the length of the slopes along the shoreline.

Based on the data of Abramov [1], the authors of [reference omitted -- tr.] attempted to establish the relationship between q and W. For this purpose, in the case of constant intensity of precipitation i_x, the absorption of water was calculated using /16
the formula of G. A. Alekseyev [2]

$$V_x = k + \frac{A}{\sqrt{t}}$$

Parameter k was established on the basis of the intensity of absorption during a long rain, after the water flow rate is stabilized.

Parameter A was determined from the condition

$$\int_0^{t\,max} q\,dt = \int_0^{t\,max} (i_x - V_x)\,dt = \int_0^{t\,max} \left(i_x - \frac{A}{\sqrt{t}} - k\right) dt, \qquad (10)$$

where t max is the time from the beginning of the rain to the end of the flood.

The instantaneous values of volume (W_t) of water on the surface of the runoff area were determined after establishment of the parameters A and k by the relationship

$$W_t = \int_0^t \left(i_x - y - \frac{A}{\sqrt{t}} - k\right) dt \qquad (11)$$

where y is the runoff per unit time, W_t is the volume of water per unit area. Comparison of the volumes produced following their averaging with respect to flow time τ from the upper end of the slope to the drainage trench showed that there is a close linear relationship between q and W. The expediency of the use of averaging ($\bar{W}_\tau$) is quite understandable, since the flow of water, according to the genetic runoff formula, consists of particles of water arriving at various times at the surface of the basin, which is more precisely reflected by the equation

$$q = \int_0^{\tau\,max} f(\tau)\phi(W_{t-\tau})\,dt, \qquad (12)$$

where f(τ) is the influence function (flow curve). This also follows from the known time sequence of arrival of precipitation (x), influx (q), volume of water (W) and runoff (Q).

Actually, even a small area consists of a tremendous number of microbasins with some accumulating capacity, the influx of which creates the main mass of the volume of water which forms the /17 water runoff to the drainage trench, i.e., on the very small scale we are concerned with a process similar to that which later occurs for the entire river network. The near-linear relationship between the volumes of water and flow rate, probably, is determined to a significant extent by the similar exponents in formulas (4) and (8). Since the relationship between the volumes of water and areas of coverage of the basin with water is nonlinear, in all probability the relationship between the influx of water q and the area of the basin is

$$q = A\omega^n, \qquad (13)$$

where n > 1.

We are now forced to utilize some hypothetical conclusions since, in spite of the tremendous importance of information on the areas of coverage with water and volumes of water for practice and for the development of the theory of formation of runoff, observational data of this type are not actually available. This indicates the great need for the performance of experimental observations in available runoff test areas and in the field, to allow us to elucidate these important aspects of the process of runoff. Systematic photography of the formation of runoff from a certain altitude in combination with measurements could be of great significance here. Until these data have been accumulated, we must limit ourselves to certain approximate solutions. As the experience of hydrological prediction has shown, the most effective results in this sense can be produced by solution of the reverse problems. In the case of interest to us, these problems can be essentially reduced to the following:

a) determination of the influx of water to the river network /18
from the area of coverage of the surface of the basin;

b) determination of the flow time and runoff to the closing line from the calculated influx. Using existing ideas of the conditions of formation of runoff, data on areas of coverage of the basin and runoff, as well as the experience accumulated in the hydrological prediction, these problems can be solved.

Actually, suppose we have a series of observations of the dynamics of the area of coverage by water and a series of the corresponding data on flood runoff. Let us assume that the relationship of q and ω can be expressed by the formula

$$q = A\omega^n \tag{13}$$

or

$$q = a\omega + B\omega^2. \tag{14}$$

We utilize the obvious condition that

$$\Sigma q = \Sigma Q, \tag{15}$$

where Q is the daily flow of water,

$$A\Sigma\omega_i^n = \Sigma Q_i \tag{16}$$

or

$$a\Sigma\omega_i + B\Sigma\omega_i^2 = \Sigma Q_i.$$

Assigning the most probable values of parameter n in the first case, let us calculate $\Sigma\omega^n$, and then construct the dependence between these quantities and the volumes of floods. The calculated parameter selected is the parameter n and corresponding

A which yield the best results. It is technically somewhat more convenient to use formula (14). Let us calculate for each flood its volume, as well as $\Sigma\omega$ and $\Sigma\omega^2$. We construct the dependence

$$\Sigma Q = f(\Sigma\omega, \Sigma\omega^2), \tag{17}$$

which is used to determine the parameters a and b.

The second problem of calculation (prediction) of the flow rate is reduced to solution of the genetic runoff formula:

$$Q(t) = \int_0^{t=\tau\max} f(\tau)q(t-\tau)\,d\tau \tag{18}$$

or

$$Q(t) = a\int_0^{t=\tau\max} f(\tau)\omega\,dt + b\int_0^{t=\tau\max} f(\tau)\omega^2\,dt. \tag{19}$$ /19

Usually, the following formulas are most commonly used for calculation of flow curves:

$$f(\tau) = \frac{1}{\tau(n-1)!}\left(\frac{t}{\tau}\right)^{n-1} e^{-t/\tau} \tag{20}$$

$$f(\tau) = a_1 \sin\frac{\pi\tau}{\tau\max} + b_1 \sin\frac{2\pi\tau}{\tau\max}. \tag{21}$$

Substituting the calculated values of q into (17), we can use methods well developed in hydrology, in particular the application of specialized modeling devices, to determine the flow curve and calculate the flow rates of the water. The problem for prediction of runoff from basins which have not been studied is reduced to establishment of the parameters n and τ, the relationship $q = \phi(\omega)$ on the basis of generalization of the results of observation for a number of basins studied and subsequent transfer of these dependences to basins not yet studied.

It should be noted that in many regions of excess moisture delivery, where the soil has high infiltration capacity, highly specific peculiarities are observed in the formation of the surface runoff. Under these conditions, the runoff is generally formed after underground water reaches the surface and fills small depressions. For these conditions, it is possible to present a simple but precise solution of the problem of prediction (calculation) of floods.

Actually, here the runoff (minus the neglibible losses to evaporation during a rain) is numerically equal to the runoff from the territory covered by water:

$$y = \omega i_x,$$

while the runoff factor $$\eta = \frac{\omega}{\omega_{tot}} i_x,$$

where y is the depth of runoff per unit time, i_x is the intensity of the rain, ω and ω_{tot} are the area covered by water and the total area of the watershed respectively.

3. Determination and Prediction of Surface Runoff on the Basis of Surface Area of the River Network /20

Over 90-95% of the entire runoff is formed by successive delivery through the gulley and ravine network and the river network to the main river. The runoff in the beds of the main and large rivers directly from their slopes is negligible.

Therefore, if we have available certain test areas allowing us to determine the flow rate before the arrival of the runoff from ravines into the river network, we could calculate the runoff of the rivers a certain time in advance, the time corresponding to the flow time from the mouths of the ravines where measurements were taken to the reference line of the river. However, direct determination of the flow rate of water in these tributaries is very difficult.

It is therefore expedient to determine a certain mean value of width of these tributaries over a portion of their length before they flow into other streams. However, we know that there is a nearly unambiguous relationship between the width of each of these tributaries and its individual flow rate. This provides the prerequisites for calculation of the total flow rate of the tributaries in this category by means of the relationship

$$q = f(\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n) \tag{22}$$

where q is the flow rate of water in the category of tributaries in question, $\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n$ are the mean widths at a certain length of the tributaries separated.

On the other hand, as we know, the flow in the final river at the point of departure from the area in question can be expressed by the formula

$$Q(t) = \int_0^{t=\tau \max} q_{t-\tau} P(\tau)\, d\tau. \tag{23}$$

Here $q(t-\tau)$ represents the summary flow rates of water in tributaries of the category in question, $P(\tau)$ is the flow curve of water from these tributaries to the end line. /21

Thus, the problem is reduced to calculation of the function $q(\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n)$, definition of the flow curve and subsequent integration of the relationships produced. The most difficult problem is determination of $q(\overline{B}_1, \overline{B}_2, \ldots, \overline{B}_n)$.

Knowledge of the hydromorphometric dependence, which is intensively studied in hydrology, can be of significant help in calculation of this function. For example, according to Velikanov:

$$\overline{B} = 5.6 \left(\frac{\overline{Q}}{\sqrt{q_i}}\right)^{2/5} . \tag{24}$$

According to S. I. Rybkin, who studied extensive observational material, we have

$$\overline{B} = 6.75\, Q^{-0.57} k^{0.13} i^{-0.07}; \tag{25}$$

in these formulas q is the flow rate of the water in a tributary and i is the slope $k = Q_i/\overline{Q}$.

In general form for any given region the flow rate of the water of its tributaries can be approximated as

$$q = AB^n, \tag{26}$$

where the exponent is near 2 in the first approximation, but must be refined if necessary. Then the influx of water can be determined from the relationship

$$q = A\Sigma\overline{B}^2 \tag{27}$$

or

$$q = A\Sigma\overline{B}^n, \tag{28}$$

substituting in (23) we produce

$$Q(t) = A\int_0^t \Sigma\overline{B}^2_{t-\tau} P(\tau)\, d\tau \tag{29}$$

or

$$Q(t) = A\int_0^t \Sigma\overline{B}^n_{t-\tau} P(\tau)\, d\tau. \tag{30}$$

Let us first test the possibility of using (29) and ordinary /22 calculation methods, and then if necessary use correction by selecting the parameters optimally corresonding to the initial data on runoff (30).

With this approach, it is quite important that the method suggested can be tested at the present time with an estimation of its accuracy based on available observation materials. Actually, if we consider a basin with a sufficiently dense network of hydrometric stations, the available water level measurements and their relationship to the width of the river can be used to determine $\Sigma\overline{B}^2$ and $\Sigma\overline{B}^n$.

Using $\Sigma\overline{B}^2(t)$ and $\Sigma\overline{B}^n(t)$ as the input functions and Q(t) as the output function, it is particularly easy to use specialized modeling devices (such as the PR-27, PR-43 and PR-49) to calculate the flow curve and estimate the accuracy of predictions. Data on the length and number of temporary streams formed during flooding may serve as a very interesting new indicator, convenient for remote interpretation. The study of the dynamics of the temporary river network is an independent and interesting problem.

On the other hand, since the total length of temporary streams $\Sigma\ell$ formed on the surface of a basin is a function of the influx $\Sigma\ell = \psi(q)$, this summary characteristic can be used to predict runoff from the basin. The use of this characteristic is primarily related to the fact that linear objects can be more easily and precisely interpreted on photographs of any scale. At the present time, however, no studies are known to us which reveal the structure of the connection between the influx of water and the length of the temporary river network.

However, as a final result we can use as our input function $\Sigma\ell(t)$, and as our output function the flow rates of water at the end line Q(t). /23

Then, the problem of prediction of runoff is reduced to determination of

$$Q(t) = \int_0^t \phi(\Sigma\ell)_{t-\tau} f(\tau)d\tau. \tag{31}$$

The use of changes not only in the temporary streams, but also in the outline of the river network (its length) to estimate the runoff is quite promising, since as the amount of water in the area increases, the length of sections of the river network visible on photographs (with otherwise equivalent conditions) should also increase significantly. Therefore, the indication properties of the river network for estimation of water content may be significant. It should be noted in particular that even after the flood passes, the darkening of river valleys can be used to establish the maximum flooding and corresponding runoff.

4. Determination of Bed Reserves and Prediction of Runoff Volume on the Basis of the Surface Area of the Stream Network

The method of prediction on the basis of bed reserves has been well developed [10], but a number of difficulties are encountered in its practical application, related both to the insufficient quantity of material available on bed morphometry, and to the comparatively sparse network of hydrometric stations.

After a rain falls, the volume of water in the small stream network increases first, after which the volume of water in the medium and large river network increases. After a comparatively short time, the main mass of the water is concentrated in the large and to some extent the medium river network. By using /24 aircraft or satellite observations, it is possible to determine the dynamics of the water surface area for small $\omega_1(t)$, medium $\omega_2(t)$ and large $\omega_3(t)$ rivers.

There is a rather close relationship between the volumes of water W and water surface area. We know further that the runoff of water Σq over a time similar to the discharge time of the entire river network or any part of it under consideration and the corresponding period of validity of prediction of τ is determined primarily by the bed reserves.

Actually,

$$\sum_0^t Q = W_0 + \Sigma q, \tag{32}$$

where W_0 is the initial reserve of water in the river network, Σq is the additional runoff through the end line from subsequent rains. The water reserves are defined as:

$$W_0 = \sum_0^t Q - \Sigma q.$$

Excluding the value of additional influx by the methods usual for hydrology, we produce a series of values of W_0. Further, for periods of time when the water is basically located in the large and medium bed network, we construct the dependences

$$W_0 = f(\omega_3, \frac{\omega_2}{\omega_3}. \tag{33}$$

Incidently, we note that due to the significant correlation between ω_3 and ω_2, the form of the connection presented above is more convenient than $W_0(\omega_3, \omega_2)$.

For periods of time when a significant portion of the water is located in the beds of small rivers ω_1, we construct the calculation dependence

$$W_0 = f(W_{0_s}, \omega_1) \tag{34}$$

here W_{0_s} is taken from (33). The transition to systemaitc information on the water surface area of rivers of various categories creates the prerequisites for significant improvement of the accuracy of runoff volume predictions.

It should be noted that since the relationship between the surface area and volume of water in many cases may be near linear, it is possible to go over to the simpler relationships $W = f(\Sigma\omega)$ and $\Sigma Q = \phi(\Sigma\omega)$, where $\Sigma\omega$ is the summary area of rivers of all categories. The additional influx Σq is considered using the ordinary methods. /25

5. Prediction and Calculation of Underground Runoff Based on Analysis of the Dynamics of Coverage of the Basin with Water and Soil Moisture Content

In case precipitation continues for an extended period of time, the flow rate of water leaving the columns of soil and entering water-bearing horizons has a quite regular form according to theoretical studies [reference omitted -- tr.]. On the other hand, when there is no influx of water to the water-bearing horizons, the level of underground water and the underground run-off decrease exponentially.

The quantity of water entering the water-bearing stratum is

$$q = \mu\frac{dH}{dt} + \mu\frac{dH_1}{dt} \tag{35}$$

where q is the influx of water in time dt, dH is the increment in the water level in time dt, dH_1 is the increment in water level taken from a curve with the reverse sign, μ is an empirical coefficient, representing the change in quantity of water in the pores as the free surface fluctuates, relative to the volume of the soil. In sandy loam soils $\mu \approx 0.1\text{-}0.15$, in loam soils $\mu \approx 0.01\text{-}0.10$.

The flow rate of water in springs not hydraulically connected to the level of a river is a function of the underground water level. Actually, for the case when evaporation of underground water can be ignored, their flow rate during the time between cycles of influx to the water-bearing horizons can be expressed by the relationships: /26

$$\frac{dW}{dt} = \mu\frac{dH_1}{dt} = Q, \tag{36}$$

where Q is the flow rate of water of a spring, related to a unit area of water-bearing stratum feeding the spring, W is the variable reserve of water in the water-bearing strata.

The situation is somewhat more complex during a period of supplementation of the underground water reserves.

However, the position here is facilitated by the fact that usually in the short periods of time studied the positive change in level is negligible in comparison to the depth of the water bearing horizon and therefore cannot significantly change the dynamic characteristics of the flow. Therefore, the mean flow rate of water from springs during the time of an increase in the level of the water table can be considered using the standard curve for exhaustion, transformed by the influx of water and the underground runoff.

If we know the influx of water q, then by using the balance method and the curve for the drop in flow rate of water of a spring, we can also calculate the course of the flow rate of water from the spring using the volume curves. Actually, the volume of water of a water-bearing horizon supplying a spring, over a certain water level corresponding to an arbitrarily taken minimum possible water flow rate, will be

$$W - W_{min} = \int_{Q_{min}}^{Q} Q(t)\, dt, \tag{37}$$

here $\int_{Q_{min}}^{Q} Q(t)\, dt$ is the area limited by the decrease curve in the interval Q and Q_{min}.

If we know the flow rates of the water and the corresponding volume $W - W_{min}$, we can calculate the volume curve $W - W_{min} = f(Q)$. /27

Performing our calculations for short time intervals, we can calculate the instantaneous volumes of water and corresponding flow rates, since the decrease curve $Q_t = f(Q_{init})$ can be easily transformed to the curve $Q_t = f(W_t)$ or $Q_t - f(W - W_{min})$.

The volumes of water necessary for such calculations can be produced from the relationship

$$W_{t+\Delta t} = W_t + (\overline{q}_{in} - \overline{Q}_t)\Delta t \tag{38}$$

here $W_{t+\Delta t}$, W_t are the volumes of water at moments in time $t+\Delta t$ and t respectively, $\overline{q}_{in}$, $\overline{Q}_t$ are the influx of water to the water-bearing strata and the flow rate of the spring respectively in time Δt according to the decrease curve.

As we calculate the underground runoff, the situation is complicated somewhat by the need to consider its interaction with the surface runoff and the time required for the underground water to flow through the river network. However, even here there are certain factors which facilitate calculation.

Actually, as was shown in the studies of B. I. Kudelin [21], during a flood or high water season, the period of removal and supplementation of the underground runoff comes to an end, these two values being similar to each other.

It is therefore expedient to calculate the underground runoff which would occur without the disrupting influence of floods, considering the study of floods to be an independent problem.

As concerns the consideration of flow time, it can be achieved using the isochrone, flow curve and other methods well developed in hydrology. Furthermore, considering the significantly /28 lower variability of underground runoff of rivers in comparison to surface runoff, the underground runoff can in many cases be considered equal to the mean value of influx to the river network in the time of bed flow.

Calculation of underground runoff can in principle be approached in the same manner as surface runoff, i.e., calculations can be performed using the Dyuamel formula

$$Q(t) = \int_{0}^{t=\tau\,max} q(t - \tau)P(\tau)\,d\tau. \tag{39}$$

Here the flow curve $P(\tau)$ can be studied by analysis of the combination of the underground runoff decrease curve and the stream bed flow curve. In a simpler solution

$$Q(t) = \int_{0}^{t=\tau\,max} \overline{q}(t - \tau)P_1(\tau)\,d\ , \tag{40}$$

where $\overline{q}(t - \tau)$ is the time-averaged bed flow, τ is the influx to the water-bearing horizons, $P_1(\tau)$ is the flow curve, calculated from the underground runoff decrease curve.

These approaches have the advantage that they reveal the genesis of the underground runoff, since they show the portions of the runoff of which it consists, based on the time of its formation. However, practical application of this method is hindered by the fact that calculations using the flow curve must be extended over a long period of time. We note in passing that the influx of underground water $\overline{q}$ can in principle be calculated from the actual course of underground runoff using the following equation:

$$\overline{q}_{in} = \frac{W_{t'+\Delta t} - W_t}{\Delta t} + \overline{Q}_t. \tag{41}$$

It was shown above that in the final analysis, the problem of calculation and prediction of the underground water mode is primarily related to the need to determine the underground water feed.

In turn, all processes of supplementation of the reserves of /29 underground water pass through the surface of the Earth, and the most intensive refilling of reserves of underground water occurs upon accumulation of water on the surface of the basin, characterized primarily by the variation in the area of the basin covered by water with time. Another important characteristics is the soil moisture content, since the intensity of seepage of water downward in the soil is directly related to it. These characteristics can be estimated using photographs of the surface of the Earth. Thus, the further task consists in direct introduction of the indicators of coverage of the basin by water and soil moisture content into the calculation plans and direct prediction of the underground water mode on this basis.

One prerequisite in the approaches studied earlier to solution of the problem of prediction of the surface and underground runoff was the attempt to avoid characteristics difficult to generalize, for example the distribution of the filtration factors, hydraulic-morphometric characteristics of basins, beds and strata, etc. This can be done by introduction of such integral characteristics of the runoff process as decrease curves, flow curves, etc., determined by observation and calculation. We note incidently that the approaches suggested may be very effective in land-reclamation hydrology and hydrogeology. As we know, calculation of surface runoff, underground feed and the level of underground water are very important in this case for establishment of irrigation norms. However, the great variety of irrigation ditches and degree of coverage with various irrigation conditions prevents any acceptable solution of these problems.

Introduction of the area of coverage of irrigated territory by water, which is closely related both to the degree of surface runoff and to the underground feed, into the calculation will hopefully allow a more precise solution to be produced. /30

6. Initial Material for Practical Utilization of the Suggested Methods of Prediction and Calculation

Initial materials can be divided into three groups: surface, aircraft and space.

Surface materials include:

a) Data from observations of runoff at end lines, levels of water, topographic materials characterizing the water surface area in streams and on the surfaces of a basin, as well as the relief of the terrain, soil, plant cover, curves relating the area of the bed to levels, soil moisture, etc. These characteristics can be partially produced by low flying aircraft, as well as photographic surveys taken from observation towers.

These materials can be used for several purposes, namely:

1) Development of a method of prediction and calculation for certain basins and runoff stations and establishment of the influence of the accuracy of elements measured on prediction error.

2) Determination of the dependences necessary for the use of remote measurements, for example establishment of the type of relationship between the area of large accumulations of water on the surface of a basin and the total area of coverage of the basin with water under various physical and geographic conditions.

3) Determination of the influence of physical and geographic characteristics of basins on the nature of the relationship /31 between measured runoff factors and the values of the factors for development of a method to make the transition from studied basins to basins not yet studied.

4) The use of these materials for interpretation of photographs from spacecraft and high-altitude aircraft.

5) Composition of certain types of predictions, particularly catastrophic floods (especially mud-laden torrents).

The resolving capacity of flight vehicles varies over an extremely broad range from 50 to 12,500 m. The scale of a photograph (m), as we know, is determined primarily by the altitude of photography (H) and the focal length of the camera used (f). If the angle of inclination of the photograph and curvature of the Earth are not considered, then: $1/m - f/H$.

For the purposes in question, flight vehicles with low orbits and particularly those with medium-altitude orbits which can provide high accuracy of observation for the small objects noted above, are of great significance.

The resolving capacity of the multispectral scanning system MSS and the television system RBV of the ERTS-1 satellite, with 6000-line image, approaches the resolution produced by piloted spacecraft from lower altitudes.

One of the most difficult problems for the production of reliable aerial photographs at any time is elimination of the influence of the cloud cover. Studies on measurement in the radio (centimeter) wave band are quite promising as concerns elimination of the influence of cloud cover. To make studies in /32
the radio frequency range, either the surface of the Earth must be illuminated with radio waves provided by a generator installed with the system, or the passive radiation of the Earth or atmosphere must be recorded (passive photographic systems). In some cases, it may be expedient to use low-flying aircraft and helicopters to eliminate the influence of cloud cover, particularly during catastrophic floods. In general, we note the great promise of the use of these aircraft for the development of prediction methods. We should also note that the factual resolution depends on brightness details of terrain elements and the transfer function of the atmosphere.

Vegetation, particularly forests, may represent a significant obstacle to determination of water surface areas. In this case, itis difficult to produce reliable results. However, forested regions almost always have some areas without heavy vegetation. It therefore seems most promising to establish the transfer functions of runoff in such areas with forested territories, allowing us to approach the solution of the more difficult problem mentioned.

For bright terrain elements and, which is particularly important for hydrology, for linear objects (rivers and ravines), they may be significantly higher. As B. V. Vinogradov and A. A. Grigor'yev [7], photographs made with a long-focus camera from Gemini-4 (scale 1:700,000) show the entire ravine-gulley network provided on a map of the state of New Mexico (scale 1:200,000) quite clearly. In the Arabian Desert, photographs taken from this satellite clearly show the branched erosion network as fine, bright threads.

Table I gives the range of characteristic dimensions of hydrological characteristics requiring remote measurement in order to use the methods of prediction suggested, according to the physical and geographic peculiarities of basins and the method of prediction.

TABLE I

Measured Characteristic	Range of Characteristic Dimensions
% coverage of basin surface by water	1000-30,000 km^2
Soil moisture content	1000-30,000 km^2
Area of individual microlakes	From a few sq. meters to few sq. km
Area of water surface of gulley-ravine network	Length 1-3 km, width 10-30 m
Water surface area of river system	Length 10-300 km, width 50-3000 m
Length of temporary streams	Hundreds of meters to a few km

In order to make the optimal decision (naturally in cases not involving human life) we should base our decisions on the condition that the difference between the savings resulting from prediction (S) and the cost of the performance of measurements and composition of the prediction (C) should be maximal $\psi(\Delta)$ = max. For this purpose, we must construct the dependence between the possible savings (S) and the error of prediction (Δ), as well as the cost involved in the construction of the prediction and in its error.

Solving the equation $S(\Delta) - C(\Delta) = \Psi(\Delta)$, we find $\Psi(\Delta)$ = max. /34
With this approach, determination of the optimal relationship between surface, aircraft and satellite measurements will be quite important, as is determination of the effective proportions between path, spot sample and continuous-coverage photographic images of the surface of the Earth.

7. Use of Remote Probing for Runoff Prediction in the USA

In the USA, work is currently being conducted on the creation of a computer system for reproduction of hydrographs of runoff from watersheds which have not been hydrologically studied, utilizing the ordinary data plus results of remote measurements, particularly satellite measurements [references omitted -- tr.].

This project is based on the assumption that a close relationship can be established between the parameters of the model describing the formation of rain runoff and the physical-geographic characteristics of a watershed, determined using remote measurements.

The project consists of three parts.

1. Development and testing on basis of observations in a well-studied region of mathematical models of runoff, the parameters of which will be found using data from remote measurements, for example aerial photographs and certain supplementary surface observations, such as data on soils. The Tennessee river valley, where there is a dense network of hydrological and meteorological stations, has been selected as the base region for study.

2. Performance of work for some other basin with a dense network of hydrometeorological stations and physical-geographic and climatic conditions differing significantly from those of the Tennessee river valley. /35

3. Testing of the model developed in a case where there is no observation of runoff for watersheds located in various parts of the Earth.

The first portion of the project was planned for completion in 1973.

The studies were based on the well-known Stanford model, allowing elementary processes of runoff formation (infiltration, surface delay, transformation of runoff hydrograph, etc.) to be reproduced and the runoff hydrograph to be calculated on the basis of observations of precipitation and evaporation. The (13) parameters of the model are found by means of optimization methods on the basis of observations of hydrometeorological factors and measurements of runoff at the end line of the watershed. In all, 35 watersheds are to be considered in the Tennessee valley. Observations of 25 watersheds will be used to determine the parameters and construct the correlation dependences of these parameters with the physical-geographic and topographic characteristics of the watersheds. Observations of 10 watersheds will be used as material for checking these dependences.

Using the models developed for the individual watersheds, an interesting theoretical and practical project was performed -- estimation of the sensitivity of the hydrographs developed to errors in assignment of parameters. These estimates allowed the preliminary requirements for accuracy of measurement of the initial quantities presented in Table 2 to be established.

TABLE 2 /36

Characteristics Studied	Required Resolution (m)	Type of Observation
Topography of basin	30	High altitude aircraft
River network	15	Same
Types and distribution of plant cover	90	Low-orbit satellites
Types of soils	30	High-altitude aircraft
Infiltration parameters	--	Surface observations
Topography and properties of river valleys	3	Surface observations or low-altitude aircraft
Precipitation	--	Surface observations
Evaporation	--	Surface observations

The problem of identification of characteristics of a watershed from aerial and space photographs represents a separate task. Here it is suggested that panchromatic, color, infrared, multispectral and other photographs be used, as well as soil, topographic and geological maps and geographic descriptions. It is assumed that as a result of performance of the project it will be possible to perform continuous remote observation of the watershed and, based on these observations, to perform computer processing of data from remote observations and predict rain-fed floods.

While rating the technological aspects of the project highly, based on considerable experience in hydrographic studies, we must predict that the accuracy of the predictions using this project will not be high, since the correlation dependences for such short series (25 to 35 watersheds) with such a large number of parameters cannot be reliable. We note that better results could be expected here from the use of the empirical relationships already accumulated in hydrology, based on incomparably more observation material.

The project in question cannot in principle improve the quality of prediction of basins already studied, since the primary /37 problem (loss of runoff) is solved by the traditional method. When this work is supplemented with new theoretical constructions and the new information is used to develop more precise methods of consideration of runoff loss, determination of water influx and the volume of bed reserves, the prerequisites can be created for a significant improvement in the quality of prediction.

8. Study of the Snow Cover and Prediction of the Spring Floods by Remote Methods

At the present time, in addition to surface observations, data from aerial photography and television images provided by satellites are being effectively used to determine the characteristics of the snow cover: the altitude of the snow line in the mountains [references omitted -- tr.] and the areas of coverage of basins with snow.

The first guides are just being published on the application of satellite photographs for the mapping of the snow cover [30].

The altitude of the snow line is directly included in certain prognostic dependences, and therefore its remote determination may be quite useful for improvement of the prediction of mountain river runoff.

As concerns the areas of coverage of the basin surface with snow, these data and particularly the data from aerial photographs can be used for calculation of the thaw runoff hydrograph. Actually, /38

$$Q_t = \int_0^{t=\tau\,max} \eta F_{t-\tau} i_{t-\tau} P(\tau)\, d\tau \qquad (42)$$

where i is the intensity of water output of the snow cover, F is the area of the basin covered with snow, $P(\tau)$ is the flow curve, η is the runoff coefficient, which depends on the soil moisture content (w), depth of freezing (H_t) and depth of the snow cover (x_t). The runoff coefficient (η) can be determined from empirical data: $\eta = f(x_t, w, H)$. The intensity of water output included in the formula can be calculated on the basis of surface observations by the thermal balance method or more approximately on the basis of the air temperature.

The soil moisture (w) can be determined from remote measurements during the period of time preceding the date of establishment of the snow cover.

The depth of freezing can be determined from agrometeorological observations. Thus, it is possible to predict the spring flood, based on a combination of remote and surface observations.

Also, we cannot exclude the possibility of determining the reserves of water in the snow cover based solely on the areas of coverage of the basin with snow and the regularities of snow thawing.

Two cases are possible here: the first is study of the map of the reduction of the snow cover over a small area using detailed photographs; the second is a study in which the resolution of the photographs is not very high, and data on the areas of coverage of the surface of the entire basin are studied. The area involved in any case is not so great that differences in the thermal mode determining the snow thaw would be significant.

In the first case, the following data can be produced: /39

1) Change of the fraction of the area of the basin covered with snow during the snow thaw period $F_s/F_{tot}\% = f(t)$.

2) Measurement of the summary depth of snow thawed (as water), calculated from surface meteorological data (for conditions of solid deposition, using methods well-known in hydrology).

3) Integral distribution curves of snow reserve $H_i = f(\overline{H}, P)$ which, according to an investigation by V. D. Komarov, are stable with time and can be produced based on materials of earlier observations. Here P is the probability of exceeding a predetermined value of snow depth (H_i).

In turn, the relationship $F_s/F_{tot}\%$, changing during the period of the thaw, is equal to P. $P = F_s/F_{tot}\%$. The horizontal lines correspond to snow depths calculated on the basis of surface data (H_i). Knowing H_i, produced from surface data, and $F_s/F_{tot}\%$, produced by remote measurement, it is not difficult to calculate the mean water reserve in the snow cover:

$$\overline{H} = \phi(H_i, F_s/F_{tot}\%) \tag{43}$$

Thus, at various moments in time we can determine the reserves in the snow cover by this method, allowing continuous checking of the calculation of snow reserves. A confirmation of the possibility of this approach to the estimation of snow reserves is provided by the studies of V. D. Komarov [15] who showed that the values of F_s/F_{tot} % produced by calculation (based on the snow thaw and integral snow distribution curves) agreed almost completely with values determined by surface observation.

The possibility of solving this problem for the second case mentioned above is less clear. Actually, for this case, due to the lower level of detail, we must study the integral distributions of mean values of snow cover over areas of different sizes. Therefore, we must determine the influence of dimensions of the territory on the form and stability of these distribution curves, and only after this can we use a method of calculation similar to that described above. The possibility of estimating snow reserves by estimating natural gamma radiation is also quite interesting. /40

Actually, soils and rocks contain natural radioactive elements, including some which radiate gamma quanta (some isotopes of uranium, thorium, and potassium 40). The gamma field up to an altitude of several hundreds of meters results from this source of gamma radiation. As it passes through the snow cover, the intensive gamma radiation is attenuated according to an exponential rule as a function of the water contained in the snow cover.

This method of measurement of moisture reserves in the snow cover, first developed by Soviet scientists [25, 26, 32], has been utilized and developed somewhat by foreign scientists [41].

Based in the data of aircraft gamma surveying performed at altitudes of 25 to 100 m, it has been found possible to produce a field characterizing the distribution of moisture reserves in the snow cover with an accuracy near the accuracy produced by surface measurement [38, 39].

The known values of the moisture reserves in the snow cover (X) determined by this remote method can be used to make long-term predictions of the spring flood. Actually, the total depth of the spring runoff (y) is approximately expressed by the equations: /41

$$y = x - p_0(1 - c^{-x/p_0}) \qquad (44)$$

or

$$y = x - p_0 \operatorname{th} \frac{x}{p_0}$$

the physical essence of the parameter p_0 is that it is equal to the maximum possible water absorption by the basin.

In turn, for regions with deep freezing of the soil, this parameter depends only on the soil moisture content.

The characteristics of soil moisture can be determined by satellite or aircraft surveys. The calculation dependence is determined from the materials of preceding observations.

Since the soil moisture usually changes little during the course of the winter, it or the index characterizing it can be assumed equal to the values based on observation immediately before deposition of the permanent snow cover.

For years when the depth of freezing is slight, as is frequently the case in regions with mild winters, a correction must be introduced for the slight freezing of the soil. It is interesting to note that, as the studies of B. D. Komarov [15] have shown, general territory-wide dependences can be constructed for extensive regions, allowing the volume of runoff to be predicted for rivers where no observations are made. As concerns the prediction of the maximum flow rate of water during the spring flood, here, as usual, it must be based on prediction of the total volume of spring runoff.

This method has been found very promising for calculation of the reserves of water on the surface of a basin and in the topmost layer of soil. This is related to the fact that the accumulation /42 of water on the surface of the basin and the moisture content of the near-surface layer of the soil down to a depth on the order of 30 cm also influence the reduction of gamma radiation, so that the change in intensity of radiation can be used to judge the moisture reserves in the upper layers of the basin, of decisive significance for the formation of the surface and underground runoff.

It is expedient to organize, together with the existing complex of hydrological observations, systematic stationary observations of the natural gamma field. This can provide new possibilities for the study and prediction of hydrological processes.

9. Some Further Problems in the Investigation of Processes of Formation of Runoff by Means of Aerial and Space Photographs

One current problem of hydrology is the use of the information provided by satellites concerning the surface of the Earth for analysis of hydrological processes.

The primary trends in the solution of this important problem are:

a) development of theoretical concepts allowing analysis of processes of formation of runoff by new methods;

b) performance of a complex of surface and high-altitude observations of the process of formation of runoff, both in order to improve the theory and in order to establish the parameters of calculation models;

c) establishment of requirements allowing the creation of an optimal system of surface and high-altitude observations, from the economic and hydrological points of view.

It would seem that the time has come to create test ranges in areas interesting in the hydrological respect, to be used for space studies, as well as special hydrological stations with a significant program of experimental studies. Such a station should include:

a) the basin of a relatively small river with detailed coverage of the topography of its surface and stream network and a system for observation of the levels and fluorates of water, the thermal characteristics and dynamics of the area of the stream network;

b) runoff areas, located in various physical and geographical conditions. Some of these should have devices for irrigation.

As additional requirements for ordinary studies, the possibility should be provided of photography of the surface as required from permanent towers, tethered balloons and stationary measurement of gamma radiation. These areas should be equipped with a detailed topographic base, as well as periodic surveys of the moisture reserves with various magnitudes of runoff.

These surface observations, in addition to their own special problems, might also be found necessary for standardized interpretation of remote observations performed over the test areas by means of satellites and aircraft.

In addition to cooperation with space and aircraft experimental investigations, these stations should also study the structure of runoff necessary for development of a theory of its formation and development of calculated prediction models.

A number of the problems of hydrological prediction formulated above can be solved only by means of high resolution photographs, /44 which would involve a significant flow of information. Therefore, we should provide for the solution of these problems by means of standard methodological developments for typical homogeneous underlying surfaces at sample test areas using images of both low and high resolution. Space photographs with low resolution should be used to determine the homogeneous physical and geographical sections to which the interpreted characteristics produced at the stations in the standardized sections can be extended.

The optimal system of test reference areas for aerial photographic surveys and space surveys with high resolution, as is the case for determination of requirements for resolving capacity of apparatus for various hydrological problems, will be determined by the results of combined satellite experiments.

In connection with the solution of a number of hydrological problems by remote methods, including fundamental problems of prediction of runoff, remote measurement apparatus must be improved both by increasing its resolving capacity and by the application of new types of surveys in ranges other than the visible light range. This trend is dictated primarily by the fact that one important hydrological characteristic is the water reserve which, be it the reserve of water in a closed body of water, in stream systems, in soil, in snow cover or in the atmosphere, is necessary both for water balance estimates and for prediction of river runoff, but cannot be determined directly from photographs in the visible light /45 range.

In this respect, the use of measurement of the natural thermal radiation in the centimeter wave band by passive and active radar methods to evaluate the moisture reserves of these hydrological objects is an aid toward significant progress in hydrology, due to the new quantitative information it produces.

The creation of the required apparatus and development of methods for quantitative estimation of the moisture reserves in the snow cover, atmosphere, soil and closed bodies of water on the basis of radiation in the centimeter wave band is a pressing problem of today, the solution of which will present great capabilities for the application of remote methods to hydrology.

Furthermore, measurements in the centimeter wave band, even with the existing low resolutions, can be of great aid in the interpretation of photographs taken in the visible light range, as additional information not subject to the influence of the cloud cover.

Problems involving the study of the condition of bodies of water, estimation of the degree of pollution and biological productivity, as well as the nature of the changes of a number of hydrological processes, for example the nature of snow thawing, can be solved using multizone surveying based on regularities of the spectral albedo of the water and snow surfaces in various states.

The development of methods for automated processing of images by computers and analog methods in order to recognize, separate, generalize and classify hydrological objects and phenomena, and also for automated production of numerical parameters, so important for hydrological predictions, may be a no less important technical problem. The application of methods of automatic pro- /46 cessing of images to hydrology is particularly important, since water resources, of all types of natural resources, are the most variable element.

The models of the prediction of hydrological characteristics presented earlier are quite schematic and need improvement. However, it seems that they might be useful, for the following reasons:

1. These models include new factors in their analysis, not analyzed in earlier runoff models.

2. The factors included in the analysis (area of coverage of the basin by water, areas of stream beds, etc.) are directly related to the runoff characteristics studied and allow calculations to be performed, bypassing such difficult-to-estimate elements as the loss of runoff and partially precipitation. Therefore, these methods present the possibility in principle of more accurate prediction than the methods usually used for prediction of runoff, based on consideration of precipitation and loss of runoff.

3. The development of the approaches studied above for the prediction of runoff stimulates the development of new experimental and theoretical studies, directly relating the structure of the surface of the basin to the structure of the runoff.

The hydrological prerequisites for predictions of runoff on the basis of photographs of the Earth's surface studied in the present article show the same capabilities which have arisen in this area of knowledge due to the development of remote methods of investigation of natural resources. Some of these capabilities can be realized in a relatively short period of time. However, /47 full utilization of the new capabilities requires detailed analysis of the fine points of determination of the hydrological characteristics from photographs made in various areas of the spectrum, in various scales and under various weather conditions, with subsequent estimation of the influence of these factors on the accuracy of prediction of runoff.

This analysis should serve as a basis for establishment of requirements toward accuracy of interpretation of photographs, accuracy of establishment of transient functions of the atmosphere and development of new methods for the study of the Earth's surface as applicable to the problems in question.

In conclusion, it must be emphasized that the variety of processes of formation of runoff, their clear sequence of development with time with phenomena of various scales, create the prerequisites for the development of a system of methods of prediction of runoff, based on phenomena with different time and space scales, occurring on the surface of the Earth. This creates favorable conditions for gradual (as the accuracy of interpretation increases) application of remote methods of measurement to the study of the processes of formation of the water mode on the continents and the predictions of runoff.

The material presented above shows that at the present time, of course when extensive studies have developed, the possibility has appeared in principle of creating a new system for composition of predictions of almost all types of runoff and methods of calculation of runoff on the basis of remote readings. This new system of prediction of runoff will constantly supplement, and in some cases where it is found to be more precise and economically suitable than existing methods, even replace the existing methods. /48

The particular value of this work lies in the fact that it presents a clear program for future studies both for purposes of further understanding of the process of formation of runoff, and also for the development of methods of calculation of runoff, based not only on surface, but also on remote methods of measurement.

The problems studied here may be useful in other areas of a rapidly developing science -- aerial and space methods of geography. A significant role in the formation of this new area was played by K. Ya. Kondrat'yev [16, 17]. Important investigations in this area are being performed at the Department of Geography of Moscow University under the leadership of K. A. Salishchev [28].

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